

# Massive Star Evolution in Different Environments<sup>1</sup>

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**Abstract.** We review the properties of massive star evolution in different environments, where the major environmental factor is metallicity. Comparisons between evolutionary models and observations of massive OB, WR stars and related objects are presented. We also review several observations asking for future improvements of stellar models and theoretical developments in this respect. We summarize evolutionary scenarios for the most massive stars and try to clarify recent questions regarding their evolutionary status as core-H or core-He burning objects.

Another environmental effect, which might affect stellar evolution is a cluster environment with a high stellar density. As test cases of massive star evolution in dense clusters we summarize recent work on the densest known resolved young clusters: R136, NGC 3603, and the three Galactic Center (GC) star clusters – the central cluster, Quintuplet and the “Arches” cluster. For the central cluster we present new comparisons between stellar parameters of emission line stars derived by Najarro et al. (1994, 1997), and appropriate evolutionary models. From their parameters we argue that most of these stars can be regarded as WNL stars, and do hence not necessarily represent a peculiar class. We suggest that some apparent differences with well known WR stars can be understood in terms of their core burning stage and/or other changes due to a high metallicity. Based on our present knowledge we conclude that in young clusters with central stellar densities up to  $\rho_c \sim 10^{5-6} M_\odot pc^{-3}$  no compelling evidence for a secondary effect influencing the evolution of massive stars has yet been found.

## 1. Introduction

Massive stars play an important role in driving the evolution of galaxies. Through their strong radiation field and their stellar winds O type stars and their evolved descendants, the Wolf-Rayet (WR) stars, are major contributors in UV radiation, mass, momentum, and mechanical energy input to the interstellar medium (ISM). They are thus an important source to ionize the ISM and power the far-

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<sup>1</sup>Invited review to appear in “Active Galactic Nuclei, Dense Stellar Systems, and Galactic Environments”, Eds. A. Baker, S.A. Lamb, J.J. Perry, ASP Conf. Series, 1998

infrared luminosities through the heating of dust. As progenitors of supernovae, massive stars are agents of nucleosynthesis, and they may provide strong feedback mechanisms acting on new star formation processes. Therefore massive star evolution is a key study in the exploration of many facets of the Universe.

While for obvious reasons all the above topics have “traditionally” been studied in our Galaxy or nearby objects, observational progress now allows us to distinguish similar processes up to very large distances and at different scales in a large variety of objects including extragalactic H II regions, IRAS galaxies, and various kinds of emission line galaxies such as starbursts and also Active Galactic Nuclei (AGN). In many of those direct or indirect signatures reveal the presence of massive stars. For the understanding of these remote and/or complex systems a good knowledge of its basic constituents (stars & gas) and the fundamental processes governing and linking them is prerequisite.

In the present review we will mainly concentrate on massive star evolution in different environments. In most astrophysical conditions the major “environmental” effect on stellar evolution is the initial composition (metallicity) of the star. In more general situations one can, however, have a multitude of mechanical and radiative effects which may influence the evolution of stars: star–star interactions (collisions, captures etc.), star–ISM interactions in a very dense interstellar medium, star–accretion disk interactions in AGN, external gravitation fields, external radiation fields etc. Such effects may indeed be of particular importance for studies of very dense stellar systems, AGN and related phenomena discussed in this volume (see e.g. the contributions of Murphy, Perry, Baker).

Our aim here is rather conservative in this respect. We first try to understand stellar evolution in simple systems (field and clusters in Local Group galaxies) and study the effects of the “environmental” effects which are the most important in these cases. It is the hope that investigations on stellar evolution in more “extreme” conditions will benefit from this understanding.

In Sect. 2 we briefly summarize IMF determinations in young clusters. We then review the physics and properties of stellar models for massive stars in Sect. 3. This section builds on the extensive review of Maeder & Conti (1994), and discusses more recent work in this field. In Sect. 4 we summarize comparisons between observations in dense young clusters and stellar evolution models. Section 5 is devoted to a detailed discussion about the massive stars in the Galactic Center star cluster.

## 2. Massive star census and IMF determinations

Stellar counts in associations are the most direct way to obtain estimates of the slope of the initial mass function (IMF). The pioneering work of Massey and coworkers using both photometry and spectroscopy provides a homogeneous approach to determine the IMF in different environments.

From analysis of nearly twenty Galactic and LMC associations they find no statistically significant variation in IMF slopes and an average value of  $\Gamma = -1.0 \pm 0.1$  for stars with masses  $M > 7M_{\odot}$ <sup>1</sup> (Massey et al. 1995b, cf. also

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<sup>1</sup>The Salpeter value is  $\Gamma = -1.35$  in this notation.

compilation in MC94). No differences are found between Galactic and Magellanic OB associations indicating that massive star formation in clusters proceeds independently of metallicity, at least over the range considered in their work. This finding is in contrast to the prevailing view (Shields & Tinsley 1976) that  $\Gamma$  becomes steeper with increasing abundance. In addition Massey et al. (1995b) do not find metallicity variations of the upper mass limit, which can reach very large values ( $M_{\text{up}} \sim 100 - 120 M_{\odot}$ ). Regarding the lower end of the mass function recent ground-based and HST observations of R136 and NGC 3603 (Hofmann et al. 1995, Hunter et al. 1995, Brandl et al. 1996, Eisenhauer et al. 1998) do not show any lack of low-mass stars. This supports the findings of Satyapal et al. (1996) who question the claims of a truncated IMF in starburst galaxies (e.g. Rieke et al. 1993). Recent reviews about the IMF can be found in the volume of Gilmore et al. (1998).

Results concerning the IMF in some dense young clusters will be briefly mentioned in Sect. 4.

### 3. Stellar evolution models and observations

#### 3.1. Input physics

A large number of grids of stellar models at different metallicities  $Z$  based on various physical assumptions have been published in the recent years (see MC94 and Maeder 1996 for a compilation). The most critical ingredients for models of massive stars discussed here are the mass loss prescription and the treatment of convection and mixing in the stellar interiors.

Since evaporation by stellar winds is dominant for stars with initial masses  $M_{\text{ini}} \gtrsim 20 M_{\odot}$  (Maeder 1991a) all model predictions are influenced by the adopted mass loss rates  $\dot{M}$ . Given the present discrepancies between observed values of  $\dot{M}$  and predictions from the radiation driven wind theory (cf. Lamers & Leitherer 1993, Puls et al. 1996, Schaerer et al. 1996a) empirical values are presently used. Most authors use those from the compilation of de Jager et al. (1988), while the newly derived empirical formulae of Lamers & Cassinelli (1996) have not been applied so far. The average mass loss rates possibly being too low (Schaerer & Maeder 1992), Meynet et al. (1994) adopted higher values, which allows a good agreement for numerous observational properties (see Maeder & Meynet 1994). Additional mixing processes (see below) might, however, also mimic a similar behaviour and hence allow to reduce the required mass loss rates.

The treatment of convection and mixing is a major uncertainty in massive stars models. Schematically the following assumptions can be identified: Schwarzschild or Ledoux criterion, core overshooting, overshooting below the convective envelope, semiconvection or semiconvective diffusion, turbulent diffusion or other forms of rotational mixing. A critical discussion of the importance of these processes can be found in MC94. In view of the large number of evidence pointing towards a need of additional mixing processes (see MC94, Maeder 1995c, and below) a more unified physical description of these processes seems required. After earlier works on this subject (e.g. Maeder 1987, Langer 1992) first progress in this direction has been made recently (Maeder 1995a, Fliegner et al. 1996, Meynet & Maeder 1997, Maeder & Zahn 1998).

In addition to the usual ingredients, WR models require specific attention on a number of points (mass loss rates, equation of state etc.). These are discussed in MC94.

### 3.2. Metallicity Effects in Massive Stars

Metallicity is a key factor which influences the evolution and hence the populations of massive stars. To be able to distinguish this effect from possible variations of star formation rates, changes of the IMF etc., one must consider the following dependences on the metallicity  $Z$  (cf. MC94):

- 1) *Nuclear production:* Compositions changes may influence the nuclear reactions. For example, in massive stars a low  $Z$  can produce a more active H-burning shell, which favours a blue location during part or the entire He-burning phase.
- 2) *Opacity effects:* Since electron scattering, which is independent of  $Z$ , is the dominant opacity source in the interior of massive stars metallicity has no important direct effect on their inner structure.
- 3) *Stellar wind:* However, in the external layers where bound-free and bound-bound opacities become important,  $Z$  has a strong influence on the opacity and hence on the atmospheres and winds. The metallicity dependence of the mass loss rates (e.g. Kudritzki et al. 1987) is the main effect by which  $Z$  influences the evolution of massive stars (Maeder 1991a).
- 4) *He content:* An increasing He content with metallicity as established from low- $Z$  H II regions (e.g. Pagel et al. 1992) has a direct effect on the models (different fuel reservoir, different interior opacity).

Before summarizing some of the main properties of massive star models at various metallicities we shall first review recent work on their pre-main sequence. Properties related to WR stars will be discussed later (see Sect. 3.5.).

### 3.3. Evolution up to the End of the Main Sequence

*Pre-Main Sequence Evolution:* Generally the pre-MS evolution of massive stars is considered to be very short (typically 1 % of the MS lifetime) and is therefore neglected in most studies. Recent observational (see e.g. Churchwell 1993, Hanson & Conti 1995) and theoretical progress (e.g. Yorke 1993, Hollenbach et al. 1994, Beech & Mitalas 1994, Jijina & Adams 1996, Bernasconi & Maeder 1996, Bonnel et al. 1998) have lead to a considerably distinct picture of the early evolution of massive stars. Here we will briefly summarize the work of Bernasconi & Maeder (1996).

Following the accretion scenario first proposed by Palla & Stahler (1990) these authors calculate the evolution of an initially  $0.8 M_{\odot}$  protostellar core until the total mass has reached typical values for high mass stars ( $\sim 60 - 100 M_{\odot}$ ). A basic parameter is the (variable) mass accretion rate, which Bernasconi & Maeder derive from the equilibrium equations of cloud models, accounting both for thermal pressure and a non-thermal support. The major results from their work are the following: 1) The accretion phase for massive stars lasts some 2-2.5 Myr, and is therefore nearly comparable to the usual MS lifetimes. 2) Newly formed massive stars with  $M \gtrsim 40 M_{\odot}$  may have already burnt a substantial fraction of their central hydrogen and hence have evolved away from the classical zero-age MS (ZAMS) at the time they emerge from their parental cloud. As

a consequence their remaining MS lifetimes are correspondingly reduced. 3) Higher turbulence in the molecular cloud leads to larger accretion rates. This in turn implies that stars of higher mass can be formed.

The second point may explain an apparent lack of O-type stars close to the formal ZAMS (Garmany et al. 1982) although this observational finding is not very well established (see Massey et al. 1995a). The last point of the scenario of Bernasconi & Maeder (1996) in particular provides interesting links between the properties of the environment and the formation and evolution of massive stars. Many implications remain to be worked out and the models have to be confronted to observations. A more consistent picture also explaining the role of ultra-compact H II regions (see e.g. Churchwell 1993) in the framework of massive star formation would be highly desirable.

*Main Sequence Evolution:* The position of the tracks in the HR-diagram and the lifetimes in the various evolutionary phases change with the metallicity  $Z$ . For massive stars at low  $Z$  the formal ZAMS is shifted to the blue and the luminosity is slightly lower for a given mass. Due to their lower luminosity and the larger initial H content, massive stars have longer H-burning lifetimes  $t_H$  at low  $Z$  (typical differences between  $Z_\odot/20$  and  $2Z_\odot$  are 35 % for a  $20 M_\odot$  star). However, lifetimes in the He-burning phase are generally shorter at low  $Z$  due to the lower mass loss rates which lead to higher luminosities in these phases.  $t_H/t_{\text{He}}$  ranges from typically 9–10 % at  $Z = 0.001$  to 11–19 % at  $Z = 0.04$  for  $M \geq 15M_\odot$ . Adopting the large mass loss rate of Meynet et al. (1994) can lead to  $t_H/t_{\text{He}}$  up to  $\sim 0.5$  at high  $Z$ . For more details we refer to the review of MC94 and references therein.

Surface abundances of He and CNO products represent extremely important tests of stellar evolution. Evidence for CN processing is available by He and N enhancements together with C depletion, while O is only gradually depleted in advanced stages of processing. The observations of Herrero et al. (1992) and Gies & Lambert (1992) show that most MS OB stars have normal He and N abundances. These elements are, however, enriched in fast rotators (Herrero et al. 1992), which suggests some additional mixing process related to rotation.

### 3.4. Post-MS evolution and Supergiants:

Very fundamental properties, like the relative lifetimes spent in the H and He-burning phases  $t_H/t_{\text{He}}$ , are quite well established. For example the comparison of Meynet (1993) with open clusters provides strong constraints on masses  $M \lesssim 20M_\odot$ . More subtle properties turn out to be the location of the He-burning stars in the HR-diagram and their surface abundances.

Indeed many problems and uncertainties remain about supergiants, for which evolution is more uncertain than for WR stars. The reason is that WR stars are dominated by powerful mass loss (“evaporation”) which overwhelms most effects related to uncertainties in convection and mixing. Supergiants are often close to a neutral state between blue and red in the HR-diagram where even small changes in convection and mixing processes can considerably alter their evolution. Let us now briefly summarize the major difficulties arising for supergiants (see also MC94).

*1) Surface abundances:* The basic result is still that by Walborn (1976, 1988) who showed that ordinary OB supergiants have He and N enrichment as a result of CNO processing, while only the small group of peculiar OBC stars have normal cosmic abundance ratios. His results are confirmed by many recent studies including Galactic OB stars (Howarth & Prinja 1989, Herrero et al. 1992, Gies & Lambert 1992), LMC stars (e.g. Lennon et al. 1991, Fitzpatrick & Bohannan 1993), and SMC B-type supergiants (Lennon et al. 1991, Lennon 1997). Thus He and N enrichment appears to be the general rule among B-supergiants, which places strong constraints on stellar evolution models.

The most simple explanation for the He and N enrichment is that the blue supergiants are on the blue loops after a first a red supergiant phase, where they have experienced dredge-up modifying the surface abundances. Difficulties of this scenario are, however, that current models do not necessarily predict blue loops of the “right” extension and at the required luminosities. More importantly the enrichment predicted by the 1st dredge-up does not seem to be high enough to account for the observations, as e.g. shown by Venn (1993, 1995). Other explanations face similar difficulties. Additional mixing processes seem thus to be required in massive stars (see Maeder 1995c).

*2) Distribution of supergiants in the HR-diagram:* There appear to be many more stars outside the MS band than predicted (see e.g. Stothers & Chin 1977, Meylan & Maeder 1982). The so-called blue Hertzsprung gap predicted by most stellar models to occur at the end of the MS does not seem to be observed. A summary of possible solutions can be found in MC94. At present the question is not settled.

*3) Blue/red ratio of supergiants in galaxies:* The observed number ratio B/R of blue to red supergiants increases with metallicity  $Z$  by typically a factor of 10 from the SMC to the solar neighbourhood (Humphreys & McElroy 1984, Langer & Maeder 1995). As mentioned earlier, the blue or red location is extremely sensitive to different model assumptions. Although generally a given set of stellar models has no difficulty of explaining the observed B/R at a given  $Z$  (e.g. through small changes of mass loss) all stellar models so far predict the opposite behaviour of B/R with metallicity (Langer & Maeder)! These authors suggest a connection of the B/R problem with internal mixing.

### 3.5. Basic properties and evolution of WR stars:

WR stars are generally considered to be bare cores which have mainly evolved from initially massive stars ( $M_{\text{ini}} \gtrsim 25\text{--}40 M_{\odot}$ ). Close binaries may also lose their outer layers from Roche lobe overflow. [For detailed reviews on WR stars see e.g. MC94 and references therein, or the recent Liège proceedings (Vreux et al. 1996)]. WR stars form the following consistent chemical sequence (E stands for early, L for late):

*WNL:* products of the CNO cycle at equilibrium with (in general) H present

*WNE:* CNO equilibrium products with no H

*WN/WC:* Rare group ( $\sim 4\%$ ), where products of both the CNO cycle and the  $3\alpha$  reaction are present (transition case, see e.g. Langer 1991, Crowther et al. 1995b)

*WCL*: He-burning products (He, C, O) present with low values of (C+O)/He

*WCE*: same but with high (C+O)/He

*WO*: same but with O ≥ C

It is important to note that this sequence is not fully described by all stars. What phases a star actually evolves through and the duration in those phases is strongly dependent on its initial mass and metallicity (cf. below).

*Evolutionary scenarios*: From recent work the following filiation scheme leading to a final SN explosion (e.g. Woosley et al. 1993, 1995) can be drawn for massive stars (cf. Maeder 1991b, 1996a, 1997, Langer et al. 1994, Crowther et al. 1995a, Crowther & Smith 1997, Pasquali et al. 1997):

$M \gtrsim 60 M_{\odot}$ :

O — Of — WNL+abs — WN7 — (WNE) — WCL — WCE — SN  
At low  $Z$ : ... WN7 — WCE — SN

$M \simeq 40 - 60 M_{\odot}$ :

O — Of — LBV + Ofpe/WN9 — WN8 — WNE — WCE — SN

$M \simeq 25 - 40 M_{\odot}$ :

O — (BSG) — RSG — (BSG) — WNE — (WCE) — SN

$M \lesssim 25 M_{\odot}$ :

O — (BSG) — RSG — BSG — RSG — SN  
YSG — SN

Parenthesis indicate uncertain or very short phases. “LBV + Ofpe/WN9” stands for an intermediate LBV phase, with Ofpe/WN9 stars (or equivalently WN9-11 according to Crowther & Smith 1997) representing a hot dormant LBV phase (see Nota et al. 1996, Crowther & Smith). According to different galactic locations (reflecting different metallicities) one has the following differences in the WR subtype evolution for  $M \gtrsim 40 M_{\odot}$ . Inner regions: WNL → WCL, outer regions: WNL → WCE → WO.

Although the evolutionary paths are quite well understood on the whole, several uncertainties and open questions remain. These will be briefly discussed in the following:

*Evolution through LBV phase ?* For  $M \gtrsim 60 M_{\odot}$  it is still not completely clear whether the most massive stars go through the LBV phases (cf. Schaller et al. 1992, Langer et al. 1994, Pasquali et al. 1997) or whether they avoid this phase (Crowther et al. 1995a, cf. also Meynet et al. 1994). LBV stars and their relations to other classes are discussed in the volume of Nota & Lamers (1997).

*Are WNL and Ofpe/WN stars core H or He burning objects ?* The previous point is also related to the question whether some WNL stars are in the core-H burning phase as already suggested early by Conti (1976). Such a scenario is indeed a natural outcome for the most massive stars given their strong mass loss (e.g. Schaller et al. 1992, Meynet et al. 1994) — no assumption is made about the burning source of WR stars in such models, and *a priori* H/He surface

abundances do not allow to determine the core burning source. In fact the models of Meynet et al. e.g. predict that at  $Z = 0.02$  all WNL stars<sup>2</sup> with  $\log L/L_\odot \gtrsim 6$  should still be core-H burning objects. This limit decreases at higher  $Z$ , which might in particular help to understand WR-like stars in the Galactic Center (see Sect. 5.)<sup>3</sup>.

Observational evidence in favour of such a scenario comes from similarities of some Of and WN spectra (Conti et al. 1995, Morris et al. 1996), analysis of the young cluster NGC 3603 and the most luminous stars in R136a (Drissen et al. 1995, de Koter et al. 1997, Crowther & Dessart 1998, see Sect. 4.), and the very high mass of a WN7 star recently measured by Rauw et al. (1996). If this is the case, the most massive O stars might well evolve directly to WNL stars and avoid the LBV phase.

An alternative evolutionary scenario including a phase of strong mass loss on the main sequence due to pulsational instabilities was proposed by Langer et al. (1994). This scenario predicts two distinct WN phases separated by an LBV phase, the first WN phase occurring during core H-burning. Although it describes well H-rich WN stars, P Cygni type LBVs (Langer et al. 1994) and might be supported by observations in R136 (Heap et al. 1994, but cf. de Koter et al. 1997), too few WN stars with low H abundance seem to be predicted (Maeder 1995b).

In the line of the Langer et al. scenario, Pasquali et al. (1997) have recently suggested the evolutionary sequence: O – Of – H-rich WNL – Ofpe/WN9, and argue that even the less massive (LMC) Ofpe/WN9 stars must be core H-burning objects. This contrasts the scenario of Crowther & Smith (1997) summarized above. We also note that in view of remaining differences in evolutionary models a different conclusion about the core burning source of the analysed Ofpe/WN9 stars is very well possible. Their claimed constraint from surface temperatures and abundances is not conclusive (see e.g. the models of Meynet et al.).

*Properties of WR stars:* The main properties of WR star models have been amply discussed by Maeder & Meynet (1994). Through the key relations for WR stars (mass-luminosity relation: Maeder 1983, mass- $\dot{M}$  relation: Langer 1989) all properties of WNE and WC stars are related (Schaerer & Maeder 1992).

The behaviour of (C+O)/He in WC/WO stars for different metallicities  $Z$  is of particular interest: At high  $Z$  (high mass loss in pre-WR phases) the He-burning core is revealed earlier in the evolution and shows thus low (C+O)/He ratios, while at low  $Z$  the He-burning core is revealed much later, i.e. with very high (C+O)/He (see e.g. Maeder & Meynet 1994). This explains nicely the following main observed properties of WC stars: 1) If WC stars exist at low  $Z$  they are of types WCE and WO, 2) WCL stars exist only at high  $Z$ , 3) At a given  $Z$ , the luminosities of WCL stars are higher than those of WCE (cf. Smith & Maeder 1991), and 4) For a given WC subtype the luminosities are higher at lower  $Z$  (cf. Kingsburgh et al. 1995).

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<sup>2</sup>The WNL phase in these models is defined by  $\log T_{\text{eff}} > 4$ . and a hydrogen abundance  $0 < X \leq 0.4$  in mass fraction.

<sup>3</sup>Additional mixing processes may also ease the formation of core H-burning WR stars

Of major importance for the understanding of WR populations is the behaviour of the lifetimes  $t_{\text{WR}}$  of WR stars as a function of initial mass and metallicity. The most important effect is a strong increase of  $t_{\text{WR}}$  with initial mass and  $Z$  (due to increased mass loss), and an increase of the threshold mass for WR formation from single stars (see Maeder & Meynet 1994). These effects are responsible for the observed increase of WR/O ratios in nearby galaxies (cf. MC94). The general increase of the WC/WN number with  $Z$  is also well accounted for. Further comparisons are found in Maeder & Meynet (1994).

#### 4. Massive Star Evolution in Clusters

Studying stellar clusters is of fundamental importance for our understanding of stellar evolution. Observations in clusters, which are thought to be formed coevally, provide the most stringent constraints on evolutionary models.

A large number of galactic open clusters with ages from 4 Myr to 9.5 Gyr was analysed by Meynet et al. (1993). Of particular interest for the evolution of massive stars is the recent work of Massey et al. (1995a) on OB associations in the LMC and SMC. Both studies find that current evolutionary models show a good agreement with observed colour-magnitude diagrams and the stellar distribution in the HR-diagram. Stronger tests could be obtained from additionally considering chemical surface abundances in these cluster/associations.

An important aim of the present work is to discuss and test massive star evolution in a particular environment, namely in dense stellar clusters. As discussed earlier these are of extreme interest for the understanding of starburst clusters, giant extragalactic H II regions, the Galactic Center (see next Section), and possibly also stellar systems in AGN. We restrict our study to the densest objects where the massive star population can still be resolved and hence stars can be analysed individually.

##### 4.1. R136 in 30 Doradus:

The massive star cluster R136 is often considered as a Rosetta Stone for starbursts (see e.g. Walborn 1991). It has been extensively observed and its stellar content has well been resolved by HST and ground-based observations (e.g. Campbell et al. 1992, Pehlemann et al. 1992, Malumuth & Heap 1994, Hunter et al. 1995, Brandl et al. 1996, Massey & Hunter 1998). Its central density is estimated to be  $\rho_c \sim 10^{4-5} M_\odot \text{ pc}^{-3}$  (Hunter et al., Brandl et al.). Some authors have found a possible flattening of the IMF towards the cluster center (Malumuth & Heap 1994, Brandl et al. 1996; but cf. Hunter et al. 1995, Massey & Hunter 1998).

From several methods (optical and IR photometry, UV and optical spectroscopy) most studies derive a cluster age of  $\sim 1-5$  Myr with a small age spread (Hunter et al. 1995, Brandl et al. 1996, de Koter 1998, Massey & Hunter 1998); the numerous most massive O3 stars and associated objects may well be very young ( $\sim 1-2$  Myr, de Koter et al. 1997, Massey & Hunter).

So far these studies show that the stellar population from  $\sim 2.8 M_\odot$  up to the most massive OB and WR stars can well be explained by standard evolutionary models appropriate to the metallicity of 30 Dor. Stringent constraints on massive star evolution is obtained from modeling observations of individual

stars. Such analysis have recently been possible in the core of R136a using GHRS spectra (Heap et al. 1991, 1994, de Koter et al. 1994, Pauldrach et al. 1994). Including the most recent study of de Koter et al. (1997) and Crowther & Dessart (1998), four stars classified as O3f/WN and WN have now been analysed quantitatively. De Koter et al. (1997) and Crowther & Dessart find that due to their huge luminosities and very strong mass loss, some of these objects have WR like spectral appearance despite appearing to be relatively H rich. The properties of these objects are found to be in good agreement with predictions for young massive core H-burning stars from Meynet et al. (1994). Interestingly the observed mass loss rates of the most luminous objects (de Koter et al. 1997) seem to be even slightly higher than the high values adopted by Meynet et al. Stronger constraints on surface abundances of members of the R136 cluster would be very useful.

#### 4.2. The Galactic starburst NGC 3603:

The central stellar mass density in the Galactic giant H II region NGC 3603 ( $\rho_c \sim 2.10^5 M_\odot \text{ pc}^{-3}$ , Hofmann et al. 1995) is comparable to or even exceeds that of R136. An early comparison between these two objects is found in Moffat et al. (1985). Recent high spatial resolution observations analysing the stellar population, IMF, and related properties have been presented by Moffat et al. (1994), Hofmann et al. (1995) and Eisenhauer et al. (1998). The stellar population and the age ( $\sim 3$  Myr) of NGC 3603 is very similar to R136. IMF slopes (for the mass range  $\sim 15\text{--}60 M_\odot$ ) of  $\Gamma = -1.4 \pm 0.6$  and  $\Gamma = -1.59 \pm 0.22$  have been derived by Moffat et al. and Hofmann et al. respectively. A discussion of the low mass population, the lower end of the IMF and comparisons with other star-forming regions is given in Eisenhauer et al. (1998).

The photometric study of Hofmann et al. (1995) shows that the individual stars (down to  $\sim 15 M_\odot$ ) can well be described by standard evolutionary models. We note that for an age this young, the recent Meynet et al. tracks can also naturally explain the simultaneous presence of O3 and WNL stars observed by Drissen et al. (1995). Some of the WN stars are then indeed expected to be in the H-burning phase as suggested by these authors. At the present state we therefore do not see compelling evidence requiring to invoke an enhancement of binaries due to the large stellar density as suggested by Tamblyn (1996). A quantitative analysis of three WR stars in the core of NGC 3603 was presented recently by Crowther & Dessart (1998).

### 5. Star clusters in the Galactic Center

Given its proximity and the possible presence of a central black hole, the center of our Galaxy deserves a particular interest for studies of nuclear activity in galaxies. Furthermore the extreme density (stellar densities of typically  $\rho_* \gtrsim 2.10^6 M_\odot \text{ pc}^{-3}$  for  $r < 0.5$  pc, Krabbe et al. 1995) and the presence of massive stars single out the central star cluster as the best laboratory to study massive star evolution in an extreme environment.

A general introduction to the Galactic Center (GC) and ample discussion about related subjects can be found in the excellent reviews of Genzel et al. (1994) and Morris & Serabyn (1996). More recent work of Genzel et al. (1996,

1997) and Ozeroy & Genzel (1996) present new dynamical studies and address the question of accretion onto the putative black hole respectively. In the context of the present contribution we will mostly concentrate on the emission line stars present in the central cluster (i.e. within  $\sim 1$  pc of Sgr A\*). The numerous late type stars and interesting questions related to their population and dynamics are e.g. discussed in Genzel et al. (1994, 1996), Blum et al. (1996) and references therein. A recent adaptive optics high angular resolution study of the stellar content near the GC is given in Davidge et al. (1997). The other major young clusters located near the GC are briefly discussed in Sect. 5.3..

### 5.1. The central star cluster

Since the discovery by Forrest et al. (1987) and Allen et al. (1990) of an unusual star (the now so-called AF star) close to Sgr A\* with broad near-IR He I/H I emission lines numerous similar sources have been discovered (Krabbe et al. 1991, Blum et al. 1995a, Krabbe et al. 1995, Tamblyn et al. 1996). Their IR luminosity, near-IR colours, and little or no CO absorption in their spectra indicate that they may be early-type stars mass losing stars. Based on their  $K$ -band spectra most of these objects were identified with Ofpe/WN9 stars (e.g. Krabbe et al. 1995) although important differences in equivalent widths and velocity widths exist (e.g. Blum et al. 1995b). These stars, also called “slash stars” (Walborn 1982, Bohannan & Walborn 1989), represent a rare class of objects, which are thought to be in an intermediate (henceforth short) evolutionary phase between massive main sequence Of stars and Wolf-Rayet (WR) stars (see Sect. 3.5.).

The presence of young massive stars in a cluster around the GC clearly indicates an important recent activity of star formation. At first sight, the large number of objects with fairly uncommon spectral appearance is, however, very surprising. The fundamental questions regarding the emission line sources are thus:

- 1) *Are these objects recently formed massive stars ?* Alternatively, and in order to circumvent difficulties related to the “hostile” conditions of star formation in the GC, Morris (1993) proposed that the He I stars are  $10 M_{\odot}$  black holes that have collided with giants. In this process they would have acquired a dense helium rich atmosphere which reprocesses the luminosity of the underlying slowly accreting black hole, and might mimic blue He I stars with mass loss.
- 2) *If 1) is true: Did these massive stars form (2a) and evolve (2b) “normally” ?* It might well be that 2a and 2b cannot be answered affirmatively. Indeed, if the very high stellar densities inferred from the number density distributions of  $2 \mu\text{m}$  sources (Krabbe et al. 1995) are correct, collisions and successive mergers of lower mass stars may form massive stars (e.g. Spitzer & Saslaw 1966, Phinney 1989). From comparisons with samples of Galactic and LMC objects, the paucity of stars with similar spectra and the rare combination of low temperature and high luminosity observed for the GC objects has also raised the question of their evolution being normal (e.g. Tamblyn & Rieke 1993, Hanson et al. 1996, Tamblyn 1996).

First we will present a new quantitative comparison of individual GC stars to address questions 1 and 2b (Section 5.2.). In a next step (Sect. 5.4.) we will

review comparisons of the stellar population with evolutionary synthesis models, which should help to shed some light on question 2a.

### 5.2. Properties and the nature of the He I emission line objects

In this Section we adopt a conservative approach. From comparisons of stellar parameters derived recently for the most luminous He I sources with those from related objects we try to answer question 1. We will then confront recent stellar evolution models with the observations of individual GC stars. If severe discrepancies between observations and our present knowledge of stellar evolution can be found, we will presume that this may imply that question 2b cannot be affirmed.

Assuming the spectra of the He I objects are formed in a spherically expanding wind of a hot star Najarro et al. (1994, 1997), and Krabbe et al. (1995) have applied the so-called “standard model” of WR stars to derive stellar parameters from fits to line profiles and the total  $K$ -band flux. So far a total of nine objects have been analysed, which we will refer to as “the GC stars” in the following. The basic parameters which can be derived are the luminosity  $L$ , the so-called “core temperature”  $T_*$  (quite strongly dependent on specific model assumptions; cf. Schmutz et al. 1992, Schaerer 1996a) the relative hydrogen and helium abundance, and the wind properties i.e. the mass loss rate  $\dot{M}$ , and the terminal velocity  $v_\infty$ .

*H and He abundances:* A rough comparison shows that these parameters are in the same range of those derived from galactic and LMC WR stars (Hamann et al. 1995, Crowther et al. 1995a, Crowther & Smith 1997). This is certainly a basic but strong argument in favour of the massive star hypothesis. The derived He abundances ( $\text{He/H} \geq 1$ , corresponding to a hydrogen mass fraction  $X \sim 0.2\text{--}0.$ ) are *higher* than those in LMC Ofpe/WN9 stars (or equivalently WN9-11 according to the reclassification of Crowther & Smith) which have  $X \sim 0.3\text{--}0.5$  (Crowther & Smith 1997, Pasquali et al. 1997). In fact the H and He abundances correspond well to the values found in late WN stars ( $\sim \text{WN6-8}$ ; Crowther et al. 1995a, Hamann et al. 1995). Abundance determinations of other elements which might bear testimony of a more exotic nature (Morris 1993) seem hardly feasible at the present times.

*Observed wind momentum:* Figure 1 (left) shows the observed radius-modified wind momentum  $\dot{M}v_\infty R^{0.5}$  of the GC stars (open squares) compared to Ofpe/WN9 (crosses and open circles) and WNL stars (WN6-8, filled squares) in the LMC (Crowther & Smith 1997, Pasquali et al. 1997)<sup>4</sup>. As shown by Puls et al. (1996) this quantity is expected to correlate with the luminosity  $L$  if the stellar wind is driven by radiation. As a comparison the relations followed by Galactic O stars (see Puls et al.) are shown by the solid and dashed lines for supergiants and LC II-V objects respectively.

The slash stars follow essentially the same relation as O stars. The same also holds for LBVs (cf. Leitherer 1997). The difference between the LMC

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<sup>4</sup>Note that these independent studies have 7 objects in common. Systematic differences are discussed in Pasquali et al.

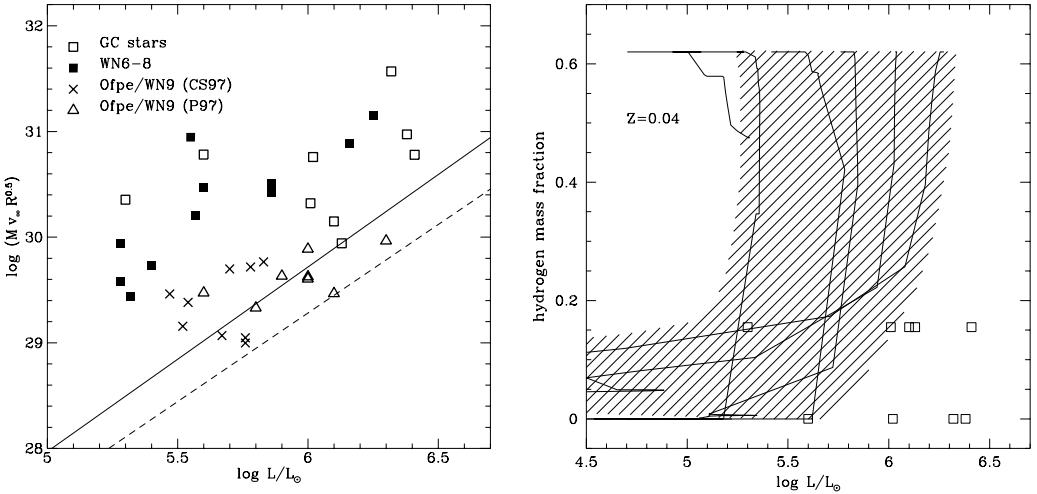


Figure 1. *Left panel:* Observed radius-modified wind momentum  $Mv_\infty R^{0.5}$  as a function of luminosity. Shown are GC stars (open squares), and LMC objects: WN6-8 stars (filled squares), and Ofpe/WN9 stars (crosses and open triangles). Sources of the observations are given in the text. *Right panel:* Comparison of predicted H-abundance versus luminosity from the high metallicity stellar models of Meynet et al. (1994) with derived values for the GC stars (open squares). The shaded band shows the domain covered by stars with initial masses of  $25 \leq M_{\text{ini}} \leq 120 M_\odot$

WN6-8 and the O stars is explained by the more advanced evolutionary stage (i.e. the higher He abundance) of the former, which – for yet unknown reasons – implies “stronger” winds (see Hamann et al. 1995, Crowther & Smith 1997). Interestingly enough the GC stars follow quite well the relation of the WN6-8 stars which may not be surprising since they share the same H/He abundances and this quantity seems to be the determining factor for the wind properties of WN stars. Contrary to the winds of O stars where metallicity effects can clearly be seen (e.g. Kudritzki et al. 1995), such a behaviour has not been found so far comparing WR stars between the LMC and the Galaxy (Crowther & Smith 1997). We verified that the same is also true for the  $L$  vs. wind momentum ratio relation derived from their sample. If the comparison between the GC stars and WNL stars is indeed appropriate we might conclude from Fig. 1 (left) that the wind properties of these objects do not show any metallicity effect even over a larger metallicity range. In fact, based on the good agreement of the *wind properties* of the He I sources with those of WNL stars (Fig. 1), one could even argue that this strongly supports the hypothesis of these sources being evolved massive stars.

*Comparison with evolutionary models:* We shall now compare the stellar parameters with predictions from the evolutionary models of Meynet et al. (1994) at a high metallicity ( $Z=0.04$ ) appropriate to the Galactic Center (Shields &

Ferland 1994). Figure 1 (right) shows the evolution of the hydrogen surface abundance as a function of the luminosity of stars with initial masses between 25 and  $120 M_{\odot}$ . The shaded band shows the domain covered by all models which evolve through the WR phase. The GC stars are shown as open squares, the majority showing fairly high luminosities compared to galactic and LMC objects, except WN stars in R136 and NGC 3603 (de Koter et al. 1997, Crowther & Dessart 1998). Due to the high mass loss, the luminosity of the most massive stars has already considerably decreased, when low values of  $X$  are reached. With the adopted mass loss prescription (which is however fairly uncertain, cf. e.g. Lamers & Cassinelli 1996, de Koter et al. 1997) it may be difficult to explain the most luminous GC stars even if an initial mass higher than  $120 M_{\odot}$  is adopted. Uncertainties in the derivation of the stellar parameters may come from the model atmospheres, which do not include line blanketing although its effect is expected to be quite strong given the high metallicity and the low temperature of the GC stars (Schaerer 1995, Schaerer et al. 1996). On the other hand it must be noted that the luminosities are derived from the  $K$ -band flux, which depends on extinction corrections, may be contaminated due to background or unresolved sources, or affected by systematic uncertainties (cf. Blum et al. 1996). In view of the uncertainties in both atmosphere and evolutionary models we think that the luminosities can still be fairly well explained by the Meynet et al. evolutionary models.

Figure 2 (left) shows the HR-diagram of the GC stars and the Meynet et al. (1994) evolutionary tracks (wind corrected  $T_{\text{eff}}$  from the tracks). Plotted are the “core temperatures”  $T_{\star}$ , which are typically 1000 to 5000 K larger than the “photospheric” values (cf. Najarro 1995). It is well known that for WR stars such comparisons are hampered by the lack of understanding the hydrodynamics of their stellar winds (see e.g. Schaerer 1996a). The comparison may therefore only be indicative. Interestingly, however, most of the GC stars are found in a relatively narrow temperature range ( $\log T \sim 4.3 - 4.4$ ) which coincides with the domain populated by the hydrogen burning WNL stars descending from the most massive stars ( $M_{\text{ini}} > 40 M_{\odot}$ ).

Overplotted on Fig. 2 (diagonal dashed line) is an estimate of the background limit at  $m_K = 11.8$  following Tamblyn (1996) assuming a black-body spectrum, the extinction law of Rieke & Lebofsky (1985), and an extinction at  $K$  equivalent to  $A_V = 30$ . This shows that (apart from red supergiants) most of the objects above this limit are expected to be hydrogen- and helium burning WN stars, while O stars above the background limit should only be found in a relatively narrow luminosity range ( $\log L/L_{\odot} \sim 5.5 - 5.7$ ). This seems to be consistent with the present lack of observed O stars (cf. Genzel et al. 1994). The indicated limit is not in conflict with the detection of evolved WC stars (Blum et al. 1995a, Krabbe et al. 1995) since their bolometric correction differs considerably from the assumed black-body value (see e.g. Blum et al. 1995a). Indeed the finding of WC stars of spectral type WC9 agrees well with the expectations from evolutionary models, which explain why late WC stars should only be found in high metallicity environments (cf. Maeder 1991a, Maeder & Meynet 1994).

*Unusual wind velocities?* As mentioned earlier, the GC stars show larger terminal velocities than the Ofpe/WN9 stars in the LMC, the average value being a factor of 2.3 larger (cf. Najarro 1995 and Crowther & Smith 1997; see also

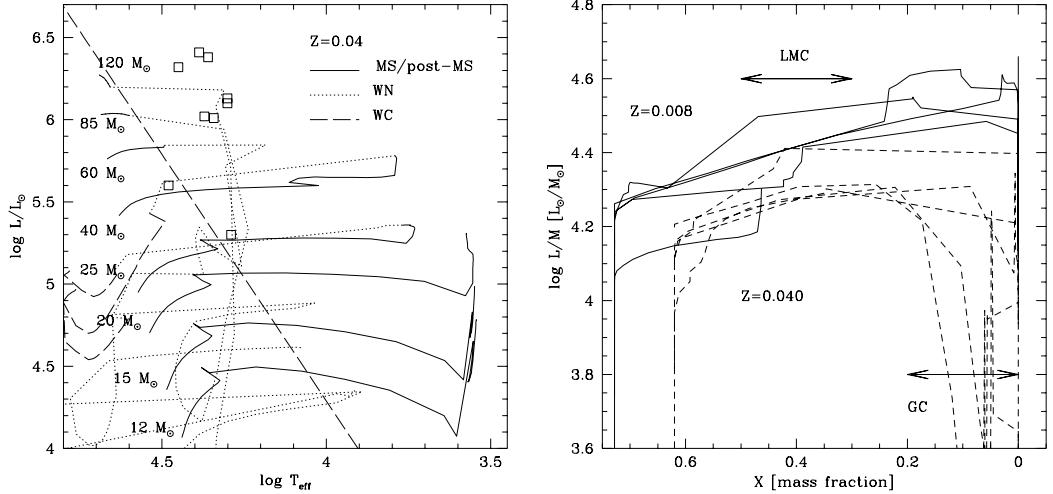


Figure 2. *Left panel:* HR-diagram comparing the GC stars (open squares) with  $Z = 0.04$  evolutionary tracks from Meynet et al. Solid lines indicate main-sequence and post-MS phases, dotted lines the WN phase (both H or He-burning), and long-dashed lines WC/WO phases. The dashed diagonal line shows an estimate of the background limit at  $m_K = 11.8$  (see text). *Right panel:* Logarithm of the luminosity to mass ratio as a function of the H surface abundance predicted for the LMC ( $Z = 0.008$  tracks, solid lines) and the GC ( $Z = 0.04$ , dashed lines). The different lines correspond to the values from the different individual stellar tracks of Meynet et al. The arrows indicate the range of the observed H abundances in LMC Ofpe/WN stars and the GC stars. The systematic differences of  $L/M$  between low and high  $Z$  tracks might explain differences in wind velocities. See discussion in the text

Blum et al. 1995b). Due to the metallicity difference one would expect only a modest increase of  $v_\infty$  ( $\sim 30\%$ ) from the radiation driven wind theory (Kudritzki et al. 1987, Leitherer et al. 1992). From a comparison of evolutionary models it appears that another largely unnoticed systematic difference between evolved stars at different metallicities may, however, explain such changes more easily as we will show in the following.

Given the lower initial H abundance and the large mass loss rates, low surface H abundances corresponding to Ofpe/WN and WR stars are attained more rapidly at high metallicity than at low  $Z$ . At a given H surface abundance the interior of WN stars will thus, on the average, be less evolved at high metallicity. This in particular implies that the luminosity to mass ratio  $L/M$  is smaller in high  $Z$  models for a given surface abundance  $X$ . Figure 2 (right) illustrates this behaviour by comparing the  $L/M$  ratio from low metallicity tracks appropriate to LMC composition (solid lines,  $Z = 0.008$ , Meynet et al.) and high  $Z$  models (dashed lines). Also shown is the abundance range determined for Ofpe/WN9 stars in the LMC and the GC stars.

The difference in  $L/M$  may have the following bearing: Since the ratio  $\Gamma = L/L_{\text{Edd}} = \kappa L/(4\pi G c M)$  of the luminosity to the Eddington luminosity is proportional to  $L/M$ , for a given opacity  $\kappa$  lower  $Z$  models have on the average larger values of  $\Gamma$  in evolved stars where H is still present. If we assume that we can at least qualitatively apply the radiation driven wind theory to these stars one expects

$$v_\infty^2 = \frac{\alpha}{1-\alpha} \frac{2GM}{R} (1 - \Gamma)$$

(Castor et al. 1975), i.e. the closer proximity to the Eddington limit implies *lower terminal wind velocities* for the lower metallicity models. We suggest that this systematic difference may, at least qualitatively, explain the larger observed terminal velocities of the GC stars compared to the Ofpe/WN9 objects in the LMC. A more rigorous quantitative understanding would not only require to account simultaneously for differences in metallicity and H/He composition but also for the apparent temperature differences which are not fully understood yet (cf. below).

*Unusual temperatures ?* The most puzzling feature of the GC stars seems to be their temperature which is lower than that of LMC and Galactic Ofpe/WN9 and WNL stars. The indication of low temperatures is primarily supported by the predominance of He I and the weakness or even absence of He II lines in the  $K$  band spectra of most objects (Blum et al. 1995b, Libonate et al. 1995). The core temperatures  $T_*$  (“photospheric” temperatures  $T_{2/3}$ ) of all GC stars analysed by Najarro (1995) and Krabbe et al. (1995) are in the range of  $T_* \sim 20 - 30.4$  ( $T_{2/3} \sim 18.8 - 28.9$ ) kK, compared to 31.2 – 35.9 (24.7 – 32.5) kK for Galactic WNL, and 27.9 – 39.4 (25.4 – 32.9) kK for LMC WNL stars (Crowther et al. 1995a, Crowther & Smith 1997). Typically both temperatures are lower by 0.1 dex in the GC stars compared to Galactic and LMC Ofpe/WN9 and WNL stars, while between the latter no significant difference is apparent.

Contrary to claims of Tamblyn et al. (1996) and Tamblyn (1996) we will now argue that a large metallicity in the GC may well play a role explaining the above differences for the following reasons: 1) Line blanketing is not included in the atmosphere models used in the analysis. As pointed out by Schaerer (1995) and Schaerer et al. (1996) blanketing is expected to be of particular importance for objects similar to the AF star and should hence be included in future spectroscopic analysis. 2) The wind properties of the GC sources might differ as would be expected if the driving mechanism of WR wind is closely related to the iron opacity peak (Schaerer et al. 1995, Pistinner & Eichler 1995). So far the comparison of wind properties (see above) does, however, not reveal any significant difference. 3) The feedback mechanism between strong wind blanketing and a thin subphotospheric convection zone pointed out by Schaerer (1996a) may maintain a larger radius. 4) Last, but not least, the temperature differences between the GC stars and Galactic/LMC WNL stars might also simply be due to differences in their evolutionary status (majority core H-burning versus core He-burning objects).

Given our poor knowledge of the winds of Ofpe/WN and WR stars, the difficulties in deriving temperatures and radii of WR stars (see e.g. Moffat & Marchenko 1996, Schmutz 1997, Schaerer 1996a), and the uncertainties men-

tioned above, we presently do not consider the temperatures of the GC stars as a strong constraint on their nature and/or evolution. Future progress on this issue would, however, be extremely interesting.

*Summary:* From previous investigations and the properties discussed above it can be concluded that the emission line objects in the GC cluster are compatible with massive evolved stars. They share the surface abundances and wind properties of WNL stars rather than those of Ofpe/WN9 stars to which they are mostly associated based on their  $K$ -band spectra. Their properties are in fair agreement with predictions from standard evolutionary models at high metallicities, which indicate that the GC stars can be both H or He burning objects. Within the remaining observational and theoretical uncertainties there is no compelling evidence that the individual stars have undergone an unusual evolution.

We note, however, that the results derived from comparisons with evolutionary models rely quite strongly on the large adopted mass loss rates  $\dot{M}$  thought to be representative for the high metallicity in the GC (cf. Shields & Ferland 1994). However, interestingly Carr et al. (1996) derived a roughly solar metallicity for the M2 supergiant IRS 7. The presence of additional mixing processes (cf. Sect. 3.) can to a certain extent have similar effects than large mass loss rates. The implications of such alternate evolutionary models will be considered in the future.

### 5.3. The Quintuplet and the Arches cluster

In addition to the central cluster two more spectacular clusters of young stars are now known: the Quintuplet cluster (= AFGL 2004) and the G0.121+0.017 (= Object 17, or “Arches cluster”, hereafter used), both located approximately within 30 pc projected distance of the GC (see review by Morris & Serabyn 1996 and references therein). After the discovery of emission line stars in the Quintuplet and the Arches cluster (cf. Nagata et al. 1990, 1995, Cotera et al. 1994, 1996) a great wealth of new data has been obtained very recently about these clusters.

The observations of Figer et al. (1996, 1998a) of the Quintuplet reveal a cluster with  $\sim 8$  WR stars and approximately a dozen other stars in earlier stages of evolution. Probably associated with it is the so-called “Pistol” star (Figer et al. 1998b, an LBV candidate of very high luminosity if single. 13 emission line stars have been identified in the Arches cluster by Cotera et al. (1996). If all emission line stars in these clusters are WR stars they represent an important increase of the known Galactic WR population (van der Hucht 1996). The mere finding of additional emission line stars similar to the one in the central cluster has also been taken as argument against their being exceptional (Cotera et al. 1996, Figer et al. 1998a).

In the recent Keck images of the Arches by Serabyn et al. (1998) massive main-sequence stars (probably OB types) have quite likely been detected for the first time in one of the GC clusters. The masses of the Quintuplet and the Arches are of the order of  $1000 - 5000 M_{\odot}$  respectively for the observed stars; extrapolation of a Salpeter IMF down  $1 M_{\odot}$  yields masses larger by factors 4-6. The Arches cluster is of similar compactness and stellar density as the central

cluster; the estimated stellar density is  $\sim 2$  order of magnitude lower in the Quintuplet (Figer et al. 1998a).

The richness in massive stars and the diversity of densities make the three GC clusters an exceptional field for studies of massive stars in different environments. While quantitative work has been done on massive stars in the central cluster all remaining objects (except the Pistol star, Figer et al. 1998b) await future analysis. New upcoming high angular resolution IR observations (*HST* NICMOS, adaptive optics work etc.) will also provide a wide field of investigation.

Let us now go back and briefly review the status of the stellar population of the central cluster as a whole.

#### 5.4. The stellar population in the central cluster

A fair number of observational constraints (number of stars of different types, total mass,  $L_{\text{LyC}}/L_{\text{bol}}$  etc.) clearly show that the GC cluster cannot be explained by a constant star formation rate and a standard IMF (e.g. Genzel et al. 1994). Burst models adapted to the GC stars have therefore been studied by Tamblyn & Rieke (1993), Krabbe et al. (1995), Schaerer (1996b), and Tamblyn (1996) and have led to differing conclusions. Although all these studies agree on the fact that recent star formation is required to describe the massive star population, Tamblyn (1996) argues that high luminosities and the spectroscopic “uniqueness” of the He I stars show that they cannot arise in such numbers from normal stellar evolution.

If the luminosity spread of the evolved WR like objects is as large as shown in Fig. 2 (left) and their evolution is “normal” they cannot be coeval. Indeed, their ages are between  $\sim 1.5$  and 5 Myr based on isochrone fitting in the HR diagram - an age spread which is roughly in agreement with that observed in young clusters (Massey et al. 1995 and Sect. 4.). Krabbe et al. (1995) find that a decaying burst beginning  $\sim 7$  Myr ago and a decay time of 3–4 Myr can explain both the population of early and late type stars very well and that the hot star cluster can well account for the bolometric and ionizing luminosities of the central parsec. However, one has to remember that the observed number of stars is still small and that less evolved main sequence stars have not been detected yet (cf. Genzel et al. 1994). In our opinion the findings summarized in this paragraph show that burst models do not allow us to identify any signs of “unusual” stellar evolution of massive stars if the history of recent star formation cannot be known better.

We conclude with a remark about less massive stars, which have not been discussed in this study: Late type stars representing an important population in the GC, show very distinct properties (see Blum et al. 1996, Genzel et al. 1996). In particular they may well indicate that collisions between red giants and MS stars might have occurred in the dense stellar core (see e.g. Sellgren et al. 1990, Genzel et al. 1994, 1996). The Galactic Center is a rich and fascinating field which many plots still to be unraveled !

**Acknowledgments.** It is a pleasure to thank the organizers and hosts of this workshop, Judith Perry, Susan Lamb, and Jayant Narlikar for their work and their hospitality which greatly contributed to the “multidisciplinary” spirit

of this meeting. I also thank Bob Blum, Claus Leitherer, André Maeder, and Nolan Walborn for useful discussions and comments.

This work was supported by the Swiss National Foundation of Scientific Research. Additional support from the Directors Discretionary Research Fund of the STScI and a travel grant from the NSF is also acknowledged. Finally I thank the Institute for Nuclear Theory at the University of Washington for its hospitality and the Department of Energy for partial support during the writing of the first version (july 1996) of this work.

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